Muon Imaging of Asteroid and Comet Interiors

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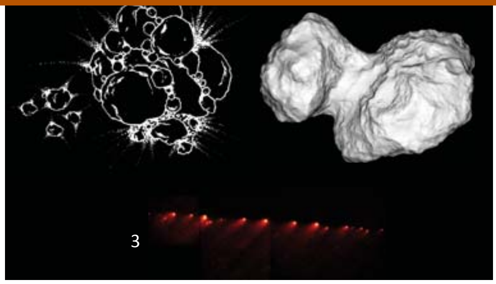
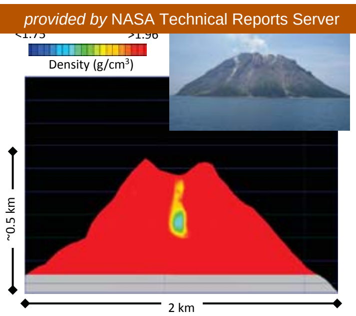
information about their internal density structure and macroporosity would provide powerful constraints on their formation and evolution as well as information needed for planetary defense, mining, and in situ resource utilization. At present, the internal structure of small bodies must be inferred from surface morphology (e.g. by optical imaging or radar) and indirectly from other observations. We are investigating new methods to directly map the deep interior structure of small solar system bodies using secondary particles, such as muons, produced by galactic cosmic ray (GCR) showers within the body itself.



1) Artist's conception of a rubble-pile cometary nucleus (from Weissman et al., 2004); 2) Surface of C-G 67P (ESA/Rosetta); 3) Breakup of Shoemaker-Levy 9 (NASA/HST) suggestive of rubble-pile structure.

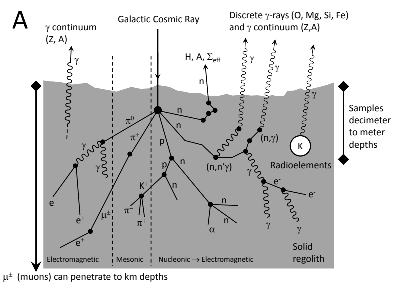


Internal structure of the Satsuma-Iojima volcano using muon radiography by Tanaka et al., 2010.

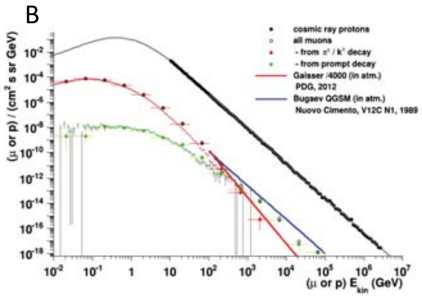
Muon production in regolith materials

Muons are charged particles, similar to electrons, but much more massive. Muons are made by the decay of mesons in galactic cosmic ray showers (**A**, **B**). Relativistic muons can penetrate large distances through rock. Muons produced in Earth's atmosphere have been detected in deep mines. Muons are made in the top meter of the regoliths of asteroids and comets. In solid surfaces, mesons often collide before decaying to produce muons. Thus, the muon source is suppressed relative to Earth's thin atmosphere and muon production depends on the density of surface materials (**C**).

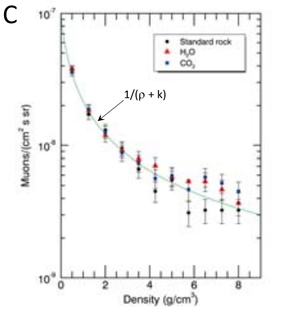
A



B



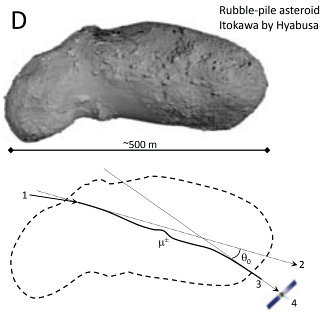
C



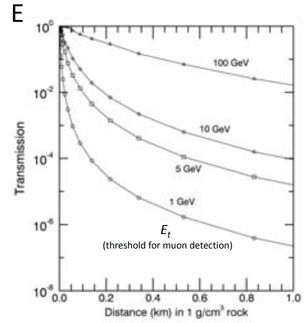
Data acquisition and reconstruction

D) The path of a high energy muon ($\mu^{\pm}$) through the asteroid is illustrated: 1) incident GCR; 2) initial direction of the muon; 3) final direction of the muon as it exits the asteroid; 4) detection of the muon by a telescope deployed on an orbiting spacecraft. The deflection of the muon is exaggerated (θ_0 is less than a few 10s of milliradians for muons that can readily penetrate the asteroid). **E**) The flux of transmitted muons arriving at the spacecraft is sensitive to the density of intervening materials. **F**) A simulated tomograph of a small, spherical asteroid reconstructed from orbital muon radiographic data reveals asteroid interior structure.

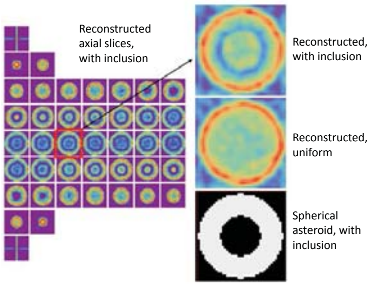
D



E



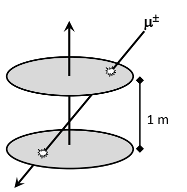
F



Telescope design

G) Conceptual diagram of a hodoscope consisting of two, position-sensitive, scintillating layers. A muon ($\mu^{\pm}$) that transects the hodoscope will produce two flashes of sensible light in coincidence. The incident direction of the muon is determined from the positions of the interactions. If a Cherenkov detector or transition radiation detector is used, then the telescope will only record muons with energies greater than a threshold (E_t). The selection E_t is critical to separate muons transmitted through the asteroid from other "upward-going" ionizing particles made on the same side of the asteroid as the hodoscope.

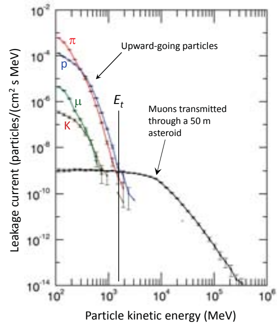
G



Muon telescope ("hodoscope")

We are investigating compact, low-cost designs that can be flown on a planetary mission.

H



Summary

Preliminary results indicate that interior contrast can be detected using a compact muon telescope with integration times ranging from hours to weeks for 100-m to 1-km asteroids, with intrinsic spatial resolution is on the order of meters. Practical limits for resolution and contrast sensitivity depend on integration time and telescope design. Regolith density within the top meter of an asteroid can be determined from radar observations. A pilot mission would combine remote radar measurements with muography of a near-Earth asteroid. Alternatively, the flux of prompt muons produced by the decay of relatively rare charmed mesons is insensitive to regolith density and may also provide information on interior structure.